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Failure and frictional sliding envelopes in three-dimensional stress space: Insights from Distinct Element Method (DEM) models and implications for the brittle-ductile transition of rock

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Rocks deformed at low confining pressure are brittle, meaning that after peak stress the strength decreases to a residual value determined by frictional sliding. The difference between the peak and residual value is the stress drop. At high confining pressure, however, no stress drop occurs. The transition pressure at which no loss in strength occurs is a possible definition of the brittle-ductile transition.

The Distinct Element Method (DEM) is used to illustrate how this type of brittle-ductile transition emerges from a simple model in which rock is idealised as an assemblage of cemented spherical unbreakable grains. These bonded particle models are subjected to loading under constant mean stress and stress ratio conditions using distortional periodic space, which eliminates possible boundary effects arising from the usage of rigid loading platens. Systematic variation of both mean stress and stress ratio allowed determination of the complete three dimensional yield, peak stress and residual strength envelopes. The models suggest that the brittle-ductile transition is a mean stress and stress ratio dependent space curve, which cannot be adequately described by commonly used failure criteria (e.g., Mohr-Coulomb, Drucker-Prager). The model peak strength data exhibit an intermediate principal stress dependency which is, at least qualitatively, similar to that observed for natural rocks deformed under polyaxial laboratory conditions.

Comparison of failure envelopes determined for bonded particle models with and without bond shear failure suggests that the non-linear pressure dependence of strength (concave failure envelopes) is, at high mean stress, the result of microscopic shear failure, a result consistent with earlier two-dimensional numerical multiple-crack simulations [D. A. Lockner & T. R. Madden, JGR, Vol. 96, No. B12, 1991]. Our results may have implications for a wide range of geophysical research areas, including the strength of the crust, the seismogenic zone and slip-tendency analysis.